

## PREDICTION OF SPATIALLY DISTRIBUTED SEISMIC DEMANDS IN STRUCTURES

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### ABSTRACT :

In this paper the efficacy of various ground motion intensity measures (IM's) in the prediction of spatially distributed engineering demand parameters (EDP's) within a structure is investigated. While the predictive capabilities of various intensity measures in predicting global seismic demands (such as peak interstorey drift over all floors) have been previously investigated, to date the effectiveness of intensity measures at predicting various measures of seismic demand occurring at spatially differing locations in a structure has not been investigated. This has direct implications to building-specific seismic loss estimation, where the seismic demand on different components is dependent on the component location in the structure. Several common intensity measures are investigated in terms of their correlation with the spatially distributed demands in a 10-storey office building, which are measured based on maximum interstorey drift ratios and maximum floor accelerations. It is found that the ability of an IM to 'efficiently' predict a specific EDP depends on the similarity between the frequency range of the IM and the vibration frequencies which control the peak value of the EDP. An IM's 'predictability' is found to have a significant effect on the median response demands for ground motions scaled to a specified probability of exceedance using the ground motion hazard curve.

**KEYWORDS:** Spatially distributed seismic demands, predictability, efficiency, ground motion selection.

### 1. INTRODUCTION

In emerging performance-based frameworks such as the PEER PBEE methodology (Cornell and Krawinkler, 2000) uncertainties in all aspects (from ground motion to loss estimation) of the seismic analysis of structures can be explicitly incorporated and propagated to obtain performance measures useful for decision making. In such a probabilistic framework, there are transparent advantages in being able to reduce uncertainties in each of the key aspects, since uncertainties inevitably result in an increase in the risk of structural failure and/or economic losses for infrequent hazards such as those posed by seismic-induced ground motion shaking.

A key area of research in the past decade has been the investigation of ground motion intensity measures (*IM*) which provide the link between the seismic hazard curve (which gives the probability/frequency of exceedance of a specific level of *IM*) and structural response (giving the distribution of the engineering demand parameter, EDP, for a given intensity, *IM*). Key aspects in the identification of an 'optimal' intensity measure is that it possesses 'efficiency' (Shome and Cornell, 1999), 'sufficiency' (Luco and Cornell, 2007), 'predictability' (Kramer and Mitchell, 2006) and 'scaling robustness' (Tothong and Luco, 2007). The aspects of efficiency and sufficiency have been studied in particular detail by Cornell and his co-workers (e.g., Baker and Cornell, 2005; Luco and Cornell, 2007; Shome and Cornell, 1999; Tothong and Luco, 2007) where the seismic response of structures was measured simply via the maximum interstorey drift over all floors (which relates well to joint rotations in structural elements and therefore the potential for structural collapse). Predictability is a relatively more recent concept which relates to the accuracy in predicting an *IM* from ground motion prediction equations. With the increased interest in ground motion selection methods (e.g., Baker and Cornell, 2006) scaling robustness seeks to determine if the distribution of EDP using scaled ground motions is biased compared with that obtained using un-scaled ground motions. Optimal intensity measures for total floor accelerations have received less attention than that of peak interstorey drifts, with the exception of Taghavi and Miranda (2003) who examined the efficiency of four different *IM*s at predicting peak floor accelerations using simple elastic structural models.

The significant spatial variation in the response of structural systems with several or more stories means that separate consideration must be given to each of these demands when considering the seismic performance of such systems rigorously within the PEER framework. As such, loss estimation methods used within the PEER PBEE framework typically employ a vector of EDPs which account for these spatially varying demands (typically interstorey drift ratios and floor accelerations). Furthermore, ground motion intensity measures are required which are efficient, sufficient, predictable and robust to scaling for this vector of EDP values.

Aslani (2005) considered the efficiency and sufficiency of four different IMs for use in predicting spatially distributed demands in structures, and this research is intended to extend the work of Aslani (2005) in the following ways: (1) Seismic hazard curves for each of the ground motion IMs are developed independently allowing explicit consideration of the predictability of the different IMs; (2) consideration is given to efficiency, sufficiency, predictability, and scaling robustness of the IMs; (3) ground motion selection based on hazard deaggregation is employed to reduce bias; and (4) 50<sup>th</sup> percentile rotation independent geometric mean (GMRotI50) intensity measures are used in both hazard computations and seismic response analysis for consistency.

The purpose of this paper is to use common IMs presented in literature, and for a specific structure investigate their predictability and efficiency in estimating peak interstorey drifts and total floor accelerations demands over all floors. As careful ground motion selection is just as important as the IM used for scaling records deaggregation of the seismic hazard is used to select ground motion records consistent with the site seismic hazard. Details of sufficiency of the IMs and their effects on loss estimation can be found in Bradley *et al.*, (Bradley *et al.*, 2008b; 2008c).

## **2. STRUCTURE CONSIDERED**

The case study structure used herein is based on the 10-storey 'Red Book building' (Bull and Brunsdon, 1998) which acts as a design example of the New Zealand Concrete Code. The primary lateral load carrying system consists of four one-way perimeter moment resisting frames which are 3 bays long. Vertical loads are transferred primarily through interior columns with gravity beams supporting one-way floor units. A 2D perimeter frame model was developed using the finite element analysis program OpenSees (McKenna *et al.*, 2004). Due to the symmetry of the structure, it was assumed that the 3D response could be reasonably approximated by separate 2D analyses in each of the two primary frame directions. The effects of foundation flexibility due to soil-foundation interaction were considered simply by using elastic rotational springs at the base of the columns. The structure was modeled using a lumped mass model and non-linear (beam) elements with the appropriate backbone properties determined using fiber-based biaxial section modelling, and stiffness and strength degradation based on calibration with experimental tests. The structural model had a fundamental period of  $T_1=1.74$  seconds. Based on a pushover analysis it was determined that the 'yield' displacement,  $d_y$ , of the structure was 10 cm (this is used for the inelastic spectral displacement IM,  $S_{di}$ ).

## **3. GROUND MOTION INTENSITY MEASURES AND SEISMIC HAZARD**

In order to investigate the prediction of spatially distributed demands in structures a variety of different ground motion IMs are selected. As there have been numerous ground motion IMs presented in the literature relating to various aspects of structural behaviour, it is necessary to apply some criteria to determine which IMs to investigate in this research. Firstly, it was desired to consider several IMs which have been used by other researchers when examining structural response from a probabilistic viewpoint. Secondly, and more importantly, all IMs used had to have a 'robust' ground motion prediction equation which can be used to develop seismic hazard curves using this IM at a variety of sites. This second point is particularly important as many studies have focused on the consideration of somewhat complex IMs which may be a combination of several 'standard' IMs in an effort to achieve better response prediction (i.e. efficiency). However, without a ground motion prediction equation for such an IM, no ground motion hazard curves can be developed. The term 'robust' has been used to differentiate IMs which have simple ground motion prediction equations based on limited data and applicability to various sites, with that of comprehensive ground motion prediction equations based on large ground motion databases and considering many features which affect ground motion prediction (e.g. faulting types, hanging wall effects, local soil and basin effects)

Based on the above criteria a total of five different ground motion IMs were considered, namely: peak ground acceleration (PGA); peak ground velocity (PGV), elastic spectral displacement (Sde); inelastic spectral displacement (Sdi); and spectrum intensity (SI). PGA and Sde can be predicted from (elastic) spectral acceleration prediction equations, some of which now also include coefficients for computing PGV (Power *et al.*, 2008). Prediction of Sdi is obtained by combining ground motion predictions for Sde with a ground motion prediction for the ratio Sdi/Sde (Tothong and Cornell, 2006). Finally, a ground motion prediction equation for SI can be computed directly from ground motion prediction equations for spectral acceleration (Bradley *et al.*, 2008a).

A simple hypothetical site with a 30-m averaged shear wave velocity ( $V_{s30}$ ) of 400 m/s was considered which is a closest distance of 15km from a 40km strike-slip fault. The fault has a Gutenberg-Richter magnitude distribution with  $\alpha = 3.0$  and  $\beta = 0.8$ ; minimum and maximum magnitudes of 5.0 and 7.5, respectively; and events assumed to be Poissonian in time. Based on this hypothetical scenario and using the Boore and Atkinson (2008) ground motion prediction equation for PGA, PGV and Sde; the prediction equation of Tothong and Cornell (2006) for Sdi; and the prediction equation of Bradley *et al.*, (2008a) for SI (with Boore and Atkinson (2008) used as the 'base' prediction equation for both Sdi and SI) ground motion hazard curves were determined (see Bradley *et al.*, 2008c for details) using the probability-based formulation of PSHA (Field *et al.*, 2003).

#### 4. GROUND MOTION SELECTION

As it is widely known that the selection of ground motion records for use in dynamic analysis can have a significant effect on the observed response then it is necessary to carefully select ground motion records for analysis to avoid bias (Goulet *et al.*, 2008). As the aim of ground motion selection is to select records for use in dynamic analysis which are representative of those which are most likely to occur at the site of interest in the future, then the target is to select a suite of ground motions which has the same distribution of ground motion properties as the deaggregation of the seismic hazard. Table 1 gives the mean moment magnitude ( $M_w$ ), (Boore-Joyner) source-to-site distance ( $R$ ), and epsilon ( $\epsilon$ ) for the five different IMs obtained by deaggregation of the seismic hazard at the 1/475 and 1/2475 annual exceedance probabilities.  $M_w$  and  $R$  obviously effect the intensity, frequency content and duration of ground motion records, and it has also been shown that when spectral ordinates are used as a ground motion IM (i.e. PGA and Sde used in this study)  $\epsilon$  also has an effect on structural response, as it relates to spectral shape (Baker and Cornell, 2005). Sdi has been shown to be (relatively) insensitive to  $\epsilon$  (when predicting peak interstorey drifts over all floors), since Sdi directly accounts for the spectral shape in the case of period elongation (Tothong and Luco, 2007). The effect of  $\epsilon$  on PGV and SI has not been researched in detail.

Table 1: Ground motion hazard deaggregation statistics and suite of 25 ground motions used.

	P(IM) = 1/475				P(IM) = 1/2475				Ground motion suite		
	IM	$\mu_M$	$\mu_R$	$\mu_\epsilon$	IM	$\mu_M$	$\mu_R$	$\mu_\epsilon$	$\mu_M$	$\mu_R$	$\mu_\epsilon$
PGA (g)	0.515	6.93	18.8	1.58	0.744	7.01	18.5	2.14	6.49	20.8	1.17
PGV (cm/s)	44.1	7.16	18.8	1.26	66.2	7.24	18.5	1.88	6.49	20.8	1.58
Sde (cm)	20.9	7.04	18.9	1.46	33.4	7.10	18.7	2.06	6.49	20.8	1.57
Sdi (cm)	20.1	7.03	19.0	1.44	31.6	7.10	18.8	2.08	6.49	20.8	1.57
SI (cm.s/s)	126.8	7.11	18.6	1.34	176.5	7.17	18.2	1.89	6.49	20.8	1.76

As the value of  $\epsilon$  depends on the IM used and cannot currently be determined *a priori* then using the deaggregation of the seismic hazard in Table 1, ground motions were initially selected based on wide range of  $M_w$ ,  $R$ , and site 30-m averaged shear-wave velocity ( $V_{s30}$ ) (specifically  $6.0 < M_w < 8.0$ ;  $0 < R < 30$  km;  $300 < V_{s30} < 800$  m/s) giving a total of 155 ground motions (each with two orthogonal horizontal components). The  $\epsilon$  values based on the five different ground motion parameters were determined and then the allowable ranges of  $M_w$ ,  $R$ ,  $V_{s30}$ , and  $\epsilon$  were further constrained (in an iterative process) to obtain a set of 25 ground motions (i.e. 50 different horizontal ground motion records for use in dynamic analysis) which were based on  $6.2 < M_w < 7.7$ ;  $10 < R < 28$  km;  $300 < V_{s30} < 600$  m/s;  $\epsilon(\text{any IM}) > 0.4$ . The ground motion records adopted are presented in (Bradley *et al.*, 2008c) and their mean statistics for the different IMs are shown in Table 1. Note that an iterative manner for selecting ground motion records was necessary as it was not possible to find a large enough suite of records which match the statistics (mean

and standard deviation) of the seismic hazard deaggregation exactly. Therefore a trade-off was required to try and match all  $M_w$ ,  $R$ , and  $\epsilon$  values relatively well.

## 5. PREDICTION OF STRUCTURAL RESPONSE: DETERMINISTIC HAZARD

Before investigating the efficacy of the five different ground motion IMs in predicting the spatially varying structural response for the 1/475 and 1/2475 probability of exceedance hazard levels, it is first necessary to (informally) test for any bias when comparing the different ground motion IMs. Potential sources of bias could be: (i) whether the selected ground motion record suite is equally representative for all five ground motion IMs; or (ii) whether the ground motion predictions equations for the different IMs used to determine the scale factors to apply to each ground motion are consistent. To investigate these points a deterministic scenario earthquake is considered with a moment magnitude of 7.0 at a source-to-site distance of 18 km (note that this is intentionally similar to the mean magnitude and distance obtained from deaggregation of the seismic hazard in Table 1). Table 2 gives the median and dispersion (lognormal standard deviation) for the ground motion IMs obtained from the ground motion prediction equations for the deterministic scenario. Figures 1a and 1b illustrate the median (specifically, the mean of the logarithms which is the median assuming a lognormal distribution) and dispersion for the GMRotI50 acceleration response spectra obtained by scaling the ground motion records to the median IM for the deterministic scenario. As the median response spectra of the 25 ground motion records scaled based on the five different IMs are very similar then it indicates that the selected ground motion suite, and the different ground motion prediction equations do not introduce any significant bias when comparing the results of the structural analyses to follow. Note that this result was expected since all of the IMs use (or are derived from) the Boore and Atkinson (2008) ground motion prediction equation, and ground motion selection to match the hazard deaggregation was used. Figure 1b provides insight into the effect of IM scaling on the dispersion in response spectra amplitudes as a function of vibration period. Obviously, PGA scales all the ground motions to have the same spectral acceleration at  $T = 0$  so the dispersion is zero at  $T = 0$ , and similarly for Sde at  $T = T_1$ . Also since the inelastic spectral displacement for this scenario,  $S_{di} = 6.09$  cm, is less than the yield displacement of the inelastic single-degree-of-freedom (SDOF),  $d_y = 10$  cm, then the dispersion is also zero at  $T = T_1$  for ground motions scaled to Sdi (the Sde and Sdi lines on Figure 1b are therefore coincident).

Table 2: Median and dispersion in the ground motion IMs for the deterministic  $M=7$ ,  $R=18$  km scenario

IM	Median, $\exp(\mu_{\ln IM})$	Dispersion, $\sigma_{\ln IM}$
PGA (g)	0.187	0.564
PGV (cm/s)	15.78	0.560
Sde (cm)	6.19	0.690
Sdi (cm)	6.09	0.672
SI (cm.s/s)	56.1	0.465

Figures 2a and 2b illustrate the median response (in terms of maximum interstorey drift ratios and maximum floor accelerations) of the case study structure based on ground motion scaling using the five different IMs. As expected, the median response, both for interstorey drifts and floor accelerations are approximately the same for all five IMs. The minor exception being that ground motions scaled based on PGA give slightly larger interstorey drifts and floor accelerations over the lower portion of the structure. This can be explained by noting in Figure 1a that for  $1.0 < T < 3.0$ s PGA scaled motions have a slightly larger median response spectra than the other four IMs. Figure 2c illustrates the dispersion in the maximum interstorey drifts for the deterministic scenario. It can be seen that over the lower half of the structure, where the peak responses are primarily due to the first mode of vibration, that Sde (and Sdi) are the most efficient (lowest dispersion) in predicting the interstorey drifts, while PGA is the least efficient. SI is marginally more efficient than PGV as it contains spectral velocity information at periods around that of the first mode. In the upper-half of the structure, where the effects of higher vibration modes are more significant, it is clearly seen that the efficiency of the spectral displacement IMs (Sde and Sdi) reduces and the efficiency of PGA increases. Figure 2d illustrates the dispersion in the peak floor accelerations for the deterministic scenario. It is apparent that PGA has the best efficiency for all floors, although the difference is less pronounced in the upper floors (where the structures dynamic characteristics have significantly modified the ground motion input at the base). On the other hand the spectral displacement IMs are the least efficient at predicting the maximum floor accelerations

over all floors.

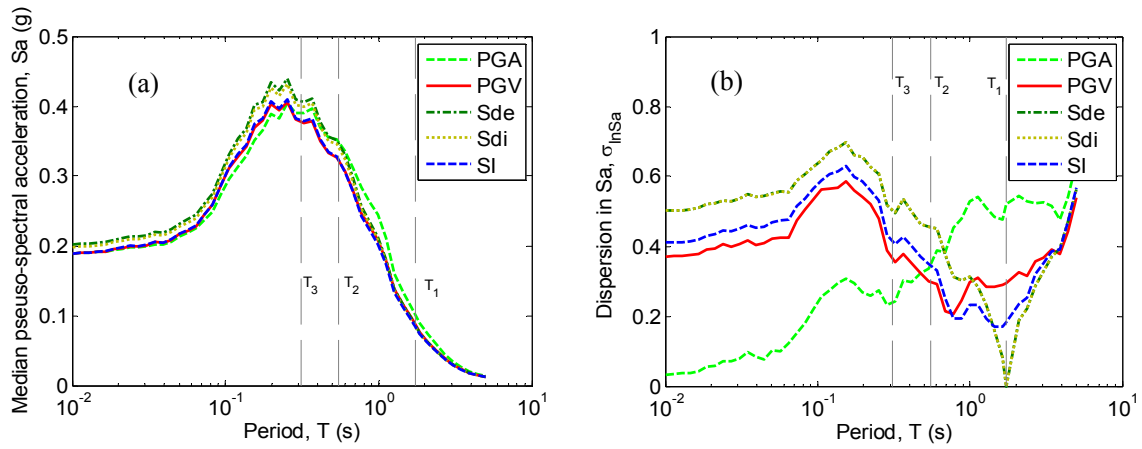


Figure 1: Response spectra of the ground motion suites scaled based on the different IMs for the deterministic scenario

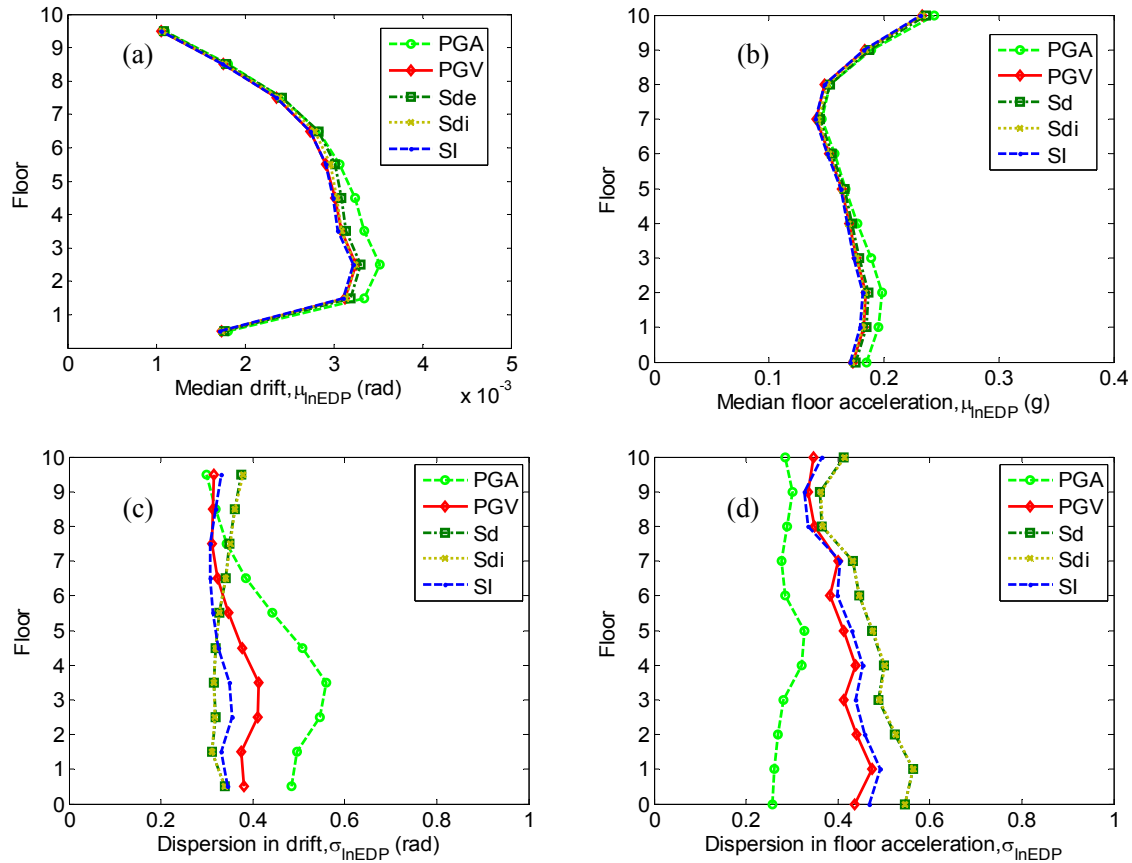


Figure 2: Median and dispersion in maximum interstorey drift and maximum floor acceleration demands for the various IMs for the deterministic scenario

The results of Figures 2c and 2d are consistent with the results obtained by Aslani (2005) and Taghavi and Miranda (2003), and clearly indicate that the ability of various ground motion IMs to predict structural response EDPs depends on the similarity of the frequency range of the motion which dominates the EDP response and the frequency range of the IM. For example, accelerations are dominated by high frequency motion so PGA is the most efficient IM, while displacements are dominated by lower frequency motion so IMs in the lower frequency region (i.e. Sde and Sdi in this case) are more efficient. The velocity IMs being in the ‘moderate’ frequency range (i.e. between accelerations and displacements) provide ‘moderate’ efficiency in predicting both maximum interstorey drifts and maximum floor



accelerations.

## **6. PREDICTION OF STRUCTURAL RESPONSE: PROBABILISTIC HAZARD**

The nature of the deterministic scenario presented in the previous section, and the fact that the consistency of the ground motion prediction equations and ground motion record suite used had negligible bias, allowed Figures 2c and 2d to be viewed solely to investigate the efficiency of the five different IMs (in this case for a relatively small level of ground motion shaking). As mentioned previously however, the determination of an optimal IM contains several other criteria, one of which is the 'predictability' of the IM. Predictability relates to the magnitude of the aleatory uncertainty in the ground motion prediction equation used to compute the ground motion hazard for a specific site. Predictability is an important property of a ground motion IM (as will be shown) since it will affect the probability of a specific level of ground motion occurring. Bommer and Abrahamson (2006, Figure 3) illustrate that the effect of a large uncertainty in a ground motion prediction equation (i.e. poor predictability) is to increase the likelihood of a specific level of ground motion intensity occurring, with the increase in likelihood becoming more significant at long return periods. As a direct indication of the predictability of the five different IMs considered here, Table 2 illustrates the dispersion in the ground motion prediction equations for the deterministic scenario considered in the previous section. As is typical, the standard deviation of a response spectral ground motion prediction equation increases with response spectral period (i.e. the predictability of Sde and Sdi is worse than PGA), while the predictability of PGA and PGV are similar. SI is observed to have a significantly better predictability than all of the other four IMs with a dispersion of 0.465. As noted by Bradley *et al.*, (2008a) this is because SI is computed from the integral (over  $T = 0.1-2.5s$ ) of the pseudo-velocity spectra, and it is known that spectral acceleration (and consequently spectral velocity) ordinates at different periods are only partially correlated.

To illustrate the effects of predictability on the results of structural response analyses the ground motion records were scaled to ground motion intensities which had 1/475 and 1/2475 exceedance probabilities, the values for which are given in Table 1. Figure 3 illustrates the median and dispersion in the maximum interstorey drifts predicted using the various IMs for both the two different exceedance probabilities. Unlike the deterministic scenario where all of the five IMs produced similar median demands, it is clear from Figures 3a and 3b that there is a significant difference when the ground motions are scaled to the same exceedance probabilities. For example, scaling ground motions to SI gives median values for the maximum interstorey drift between the 2<sup>nd</sup> and 3<sup>rd</sup> floors of 0.75% and 1.05% at the two different exceedance probabilities compared to 1.1% and 1.6% using ground motions scaled to Sde. It should be clear that the relative magnitude of the median values of the maximum interstorey drifts between the different IMs is directly related to the predictability of the different IMs. Figures 3c and 3d illustrate the dispersion in the maximum interstorey drifts obtained using the five different IMs at the 1/475 and 1/2475 exceedance probabilities. The trends regarding efficiency in predicting maximum interstorey drifts are similar to those for the deterministic scenario with the key difference being that as the intensity of the ground motion increases inelastic response causes changes in the vibration characteristics of the structure. These changing vibration characteristics subsequently affect the efficiency in predicting the EDPs at different locations in the structure. For example, comparing the dispersion in the interstorey drifts at the 1/475 and 1/2475 exceedance probabilities illustrates that increasing inelastic behaviour reduces the dispersion in the prediction of the interstorey drifts in the lower half of the structure (where most of the inelastic action is occurring) and increases the dispersion in the upper floors.

Figures 4a and 4b illustrate the median values of the maximum floor accelerations for the various IMs. Similar to the median values of the interstorey drifts, it is observed that the relative magnitude of the maximum floor accelerations is directly related to the predictability of the IMs, with SI giving the lowest maximum floor accelerations over all floors for both exceedance probabilities considered. Comparison of Figure 2b, 4a and 4b illustrate the change in the spatial distribution of the peak floor accelerations as the ground motion intensity increases. For the aforementioned deterministic scenario the largest floor accelerations occur at the top of the structure due to the presence of significant higher mode effects. However as the ground motion intensity increases, inelastic behaviour in the lower floors of the structure (which causes an elongation in the effective period of the structure) effectively acts as a filter on the high frequency components of the ground motion which cause the large accelerations in the upper floors. The same logic also explains why the maximum interstorey drift demands in the upper floors of the structure reduce (relative to the maximum interstorey drifts in the lower floors) as the ground motion intensity increases. Figures 4c and 4d illustrate the dispersion in the prediction of the maximum floor accelerations at the 1/475 and 1/2475 exceedance probabilities. Similar trends are observed compared to the deterministic scenario with PGA being the most efficient IM and spectral displacements the worst. However, due to significant inelastic

behaviour at the 1/2475 exceedance probability, it is seen that the efficiency of PGA in the upper floors reduces (as inelastic behaviour on lower floors ‘filters’ out the high frequency motion) and the velocity IMs (PGA and SI) are of a similar efficiency to PGA.

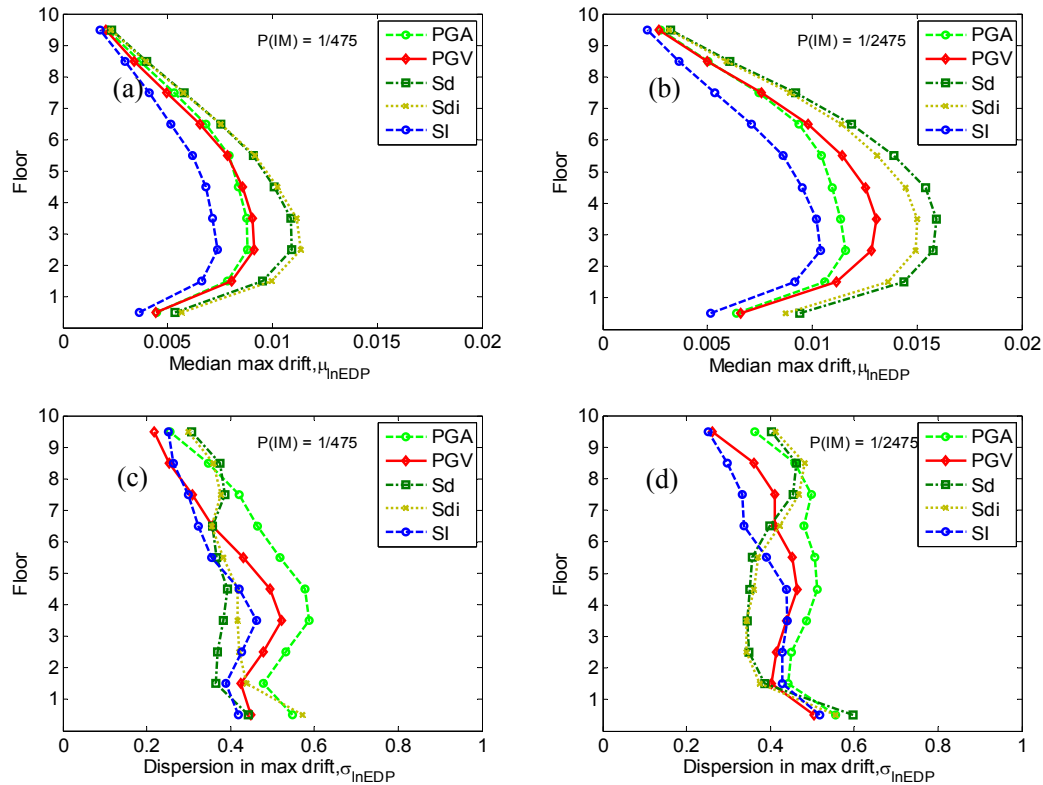


Figure 3: Median and dispersion is the maximum interstorey drifts for ground motions scaled to the 1/475 and 1/2475 exceedance probabilities using the various IMs.

It is interesting to observe in Figures 3 and 4 that there is little difference between the predictive capacity of Sdi and Sde for the case study structure considered. Comparison with the results of Tothong and Luco (2007, Table 2) however illustrates that Sdi provides little improvement over using Sde for structures with fundamental period above 1.5 seconds.

Figures 3a, 3b, 4a and 4b have illustrated that for a given exceedance probability, a significant reduction in the median response (specifically for this structure), both interstorey drifts and floor accelerations, can be obtained by using a predictable intensity measure such as SI. This has direct applications to current code-based implementations for time-history analysis which require that the average response be used for design if seven or more ground motion records are used (e.g., Beyer and Bommer, 2007; Standards New Zealand., 1995). Note that design codes state that the ‘average’ of the structural responses from the different ground motions should be used, where it is assumed that ‘average’ refers to the mean of the responses (and not the mean of the logarithms of the responses used here to get the ‘median’). However, since for a lognormal distribution the ratio of the mean to the median is  $\exp(\sigma_{\ln X}^2 / 2)$ , where  $\sigma_{\ln X}$  is the dispersion, then it was found that SI still gives the lowest ‘mean’ responses for the seismic response analyses presented here.

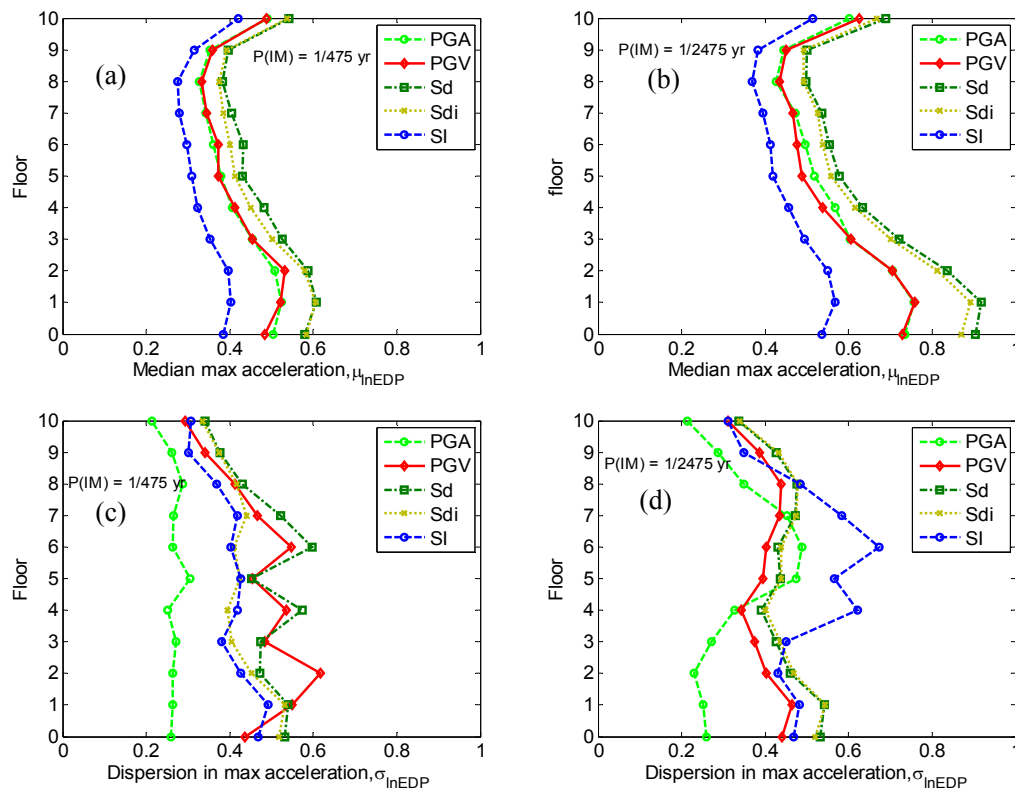


Figure 4: Median and dispersion of the maximum floor accelerations for ground motions scaled to the 1/475 and 1/2475 exceedance probabilities using the various IMs.

## 7. CONCLUSIONS

Prediction of the dynamic seismic response of multi-degree-of-freedom structures is a complex task due to the spatially distributed seismic demands which are sensitive to different frequency contents of the input ground motion records. Within the probabilistic framework of performance-based earthquake engineering it is advantageous to select and scale ground motion records with the intent to minimise the dispersion and reduce the bias in the observed distribution of the seismic response. With that goal in mind, this paper investigated the efficacy of five different ground motion intensity measures (IMs), for which robust ground motion predictions are available. The concepts of predictability and efficiency were investigated for each of the IMs when applied to the seismic response analysis of a 10-storey frame structure. It was illustrated that the efficiency (dispersion in the seismic response analysis results) of an IM can be qualitatively determined based on the frequency range of the IM compared to the frequency range of motion which controls the peak values of the EDP being monitored. The predictability (dispersion in the ground motion prediction equation) of an IM was clearly shown to be an important property in reducing the median response demand for ground motions scaled to an IM with a given probability of exceedance. Ground motion IMs (namely spectrum intensity, SI) which are predictable result in lower median seismic demands when ground motions are scaled to a specific probability of exceedance using a seismic hazard curve.

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